AN EMPIRICAL MATCH FILTER STUDY WITH CENTRAL ASIAN AND SOUTH PACIFIC EVENTS

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ABSTRACT

Two suites of events, one in the Tonga Islands and the other in the Hindu Kush, were match filtered to determine relative enhancement in signal-to-noise ratio achieved by various procedures. It was found that match-filter S/N enhancement depends very little on the proximity of the reference event used as a match filter for distances as great as 600 km. For both regions, one event with high S/N ratio performed as well as many closer events in match filtering. Pre-whitening the real signals from zero to the folding frequency before using them as matched filters resulted in serious S/N decreases on the output unless band-pass filtering was applied simultaneously to the signal band, approximately 15 to 50 seconds. A linear chirp waveform worked as well as a real waveform for the Asian events, but it was inferior to real waveforms in the Pacific. A synthetic filter constructed using Canadian-Shield phase velocities worked nearly as well on Central Asian earthquakes as real reference events.

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INTRODUCTION

This study has been carried out to further understanding of match filtering, the value of which has already been established by Alexander and Rabenstine (1967) and Alexander and Lambert (1971) for the case of long-period surface waves. They showed that it increases signal-to-noise ratio and thus lowers detection thresholds and that it provides a reliable estimate of the energy in the filtered wave train relative to that in the match-filter wave train as well as reliable spectral estimates for weak signals. Each of these desirable results imposes a different requirement on the waveform of the match filter to be used. Increase in S/N ratio requires a filter as long as possible because S/N improvement is directly proportional to the signal length; relative magnitude determination requires a close waveform match between the filter and the signal to be measured so that the correlation coefficient is high; and spectral estimation requires a pre-whitened match filter to give stable spectral estimates. As Binder (1970) has shown, there is a tradeoff between S/N ratio and correlation coefficients because correlation coefficients tend to decrease with signal length while S/N ratios tend to increase with signal length (up to some limit, of course).

This report stresses the detection threshold aspect, and results are given in terms of S/N improvement for various match filters applied to a suite of recorded signals. Two questions are investigated in detail: 1) the relative merit of using real signals instead of artificial waveforms as match filters, and 2) the degradation of S/N ratio with increased separation between the location of the match-filter event and that of the event to be filtered. Knowledge of the latter would indicate the spacing, and hence number, of real signals needed to cover a given area of interest for purposes of match filtering. Binder's (1970) study suggests that in the Kuril Islands this number may be large if any S/N improvement with match filters is to be gained.

DATA USED

We chose two source areas for investigation -- the Hindu Kush and the Tonga Islands. For simplicity we will refer to these as "Asian" and "Pacific". Only recordings of Rayleigh waves by the Z1 sensor (long-period vertical component) at the Tonto Forest Seismological Observatory in Arizona were used in this analysis. We selected approximately 50 shallow (<100 km) events for both source areas and digitized them at a rate of one sample per second. Many events subsequently had to be deleted because of tape noise, interference from calibrations or other events, and failure to time accurately the digitized event. Several well-recorded events at wide intervals in both areas were designated as reference events. Table I lists pertinent information on the final 32 events from the Pacific used in the subsequent analysis. Reference events are represented by numbers, the others by letters; and these codes will be used henceforth. Figure 1 shows the areal distribution of these Pacific events. Table II lists the final 25 events used from the Asian region, again with code numbers or letters; and Figure 2 shows the locations. All epicenter information is taken from NOS listings. The maximum dimension of the area enclosing the suite of events in both cases is about 1000 km. Reference events are separated typically by 200-300 km. We reproduce in Figures 3 and 4 the waveforms of the reference events used from the Pacific and Asian regions. An attempt was made to choose reference events with high S/N ratios, but the requirement of even distribution demanded that a few reference events with lower S/N ratios be chosen. The remainder of the events, not shown, had signals ranging from some with excellent S/N ratios to some undetectable by eye. To eliminate some noise before match filtering, the events to be match filtered were all put through a phaseless digital band-pass filter with corners at .015 and .065 Hz and slopes of 24 db/octave.

To illustrate the dissimilar dispersion characteristics of the two types of path to TFO (mostly continental for the Asian events and mostly oceanic for the Pacific events), we measured the arrival times of peaks and troughs and computed group velocity in the classical manner for one strong signal from each region. The group velocity curves are shown in Figure 5.

PROCEDURES

The Seismic Data Laboratory (SDL) program for match filtering, COLLAPSE, was used throughout. Transformations were performed by a fast Fourier transformation subroutine, and filtering was done in the frequency domain. All spectra were computed from zero to folding frequency (0 to .5 cps). The program calculates a S/N ratio on the output to which this report will refer throughout. This quantity is the largest amplitude in a one-minute window surrounding the expected peak in the output over the rms amplitude of the output in a ten-minute window well beyond this peak.

The operations performed on both suites of events are nearly the same and are as follows:

1) All of the events were first match filtered with the nearest reference event. Use of the nearest reference event should provide the optimum S/N ratio enhancement assuming that all reference events are not distorted by background noise. This step provides a base S/N ratio for each event.
2) We attempted to improve the match of the reference events to their surrounding events by modifying them to eliminate the effect on the waveform of a difference in epicentral distance between the reference event and the filtered event. This amounts to multiplying the Fourier transform of the reference event by a factor

$$D(\omega) = e^{\frac{\pm i\omega r}{C(\omega)}}$$

where r is the difference in epicentral distance and C is the phase velocity. The sign of the exponent depends on whether the reference event is further from or closer to TFO than the event to be filtered. The phase velocity curve was not known for the two areas, and so assumed curves as given in Table III were used. The dispersion curve for the Tonga Islands is basically an oceanic type, with some reduction in velocities to reflect the presence of the island structures in that area. The dispersion curve for the Hindu Kush is continental.

We expect that modifying the match filter for dispersion effects will only be of value when the distance between the reference event and the event to be filtered is of the order of hundreds of kilometers. Alexander and Rabenstine (1967) have investigated this effect with synthetic seismograms and found that the correlation coefficient between Rayleigh-wave signals dropped only to 0.8 for events separated by 1000 km (simulated to be 3000 and 4000 km from an observation point).

3) We then selected one reference event to filter all of the events in the area. The reference event was first used in its original form and then was modified to correct for the differences in epicentral distance between it and the filtered events. These differences were as much as 600 km, and we expect that the improvement over use of the unmodified filter might become significant.

4) Using the one selected reference event again, we whitened its amplitude spectrum from zero to the folding frequency. The modification for dispersion effects appropriate to each filtered event was retained. The whitening is accomplished by replacing A and B in the complex point A + iB of the spectrum with

$$A' = A/(A^2 + B^2)^{1/2}$$

$$B' = B/(A^2 + B^2)^{1/2}$$

This produces a constant amplitude spectrum of unit height.

5) We also designed chirp filters for both areas according to the formula

$$f(t) = \sin[2\pi t(\frac{1}{T_0} + \frac{\frac{1}{T_1} - \frac{1}{T_0}}{\frac{1}{C_1} - \frac{1}{C_0}} \cdot \frac{T}{2\Delta})] \quad 0 < T < \Delta\,(\frac{1}{C_1} - \frac{1}{C_0})$$

where

T_0 = longest period in signal,

T_1 = shortest period in signal,

C_0 = group velocity for longest period,

C_1 = group velocity for shortest period,

Δ = epicentral distance.

The chirp filter is a swept-frequency waveform in which group delay time is a linear function of frequency. We then expect the chirp filter to perform well when the signals to be filtered closely approximate this relation in their own dispersion.

RESULTS

Pacific events

All of the lettered events in Table I were first match filtered with the nearest reference event, in its original form, to provide the base S/N ratios which are listed in column I of Table IV. These results are for a match-filter length of 512 secs. Output S/N ratios for a longer filter, 1024 secs, were definitely lower in almost all cases; no attempt, however, was made to find some optimum length between 512 and 1024 secs. All further results for these Pacific events using real signals are for lengths of 512 secs also.

The next step was to modify the reference events in the manner described in the previous section to account for the differences in epicentral distance. The epicenter separations are given in Table V. The results of modifying the six reference signals used previously and then filtering the same events again are given in column II of Table IV in the form of S/N improvement in db relative to the base S/N ratios given in column I for the unmodified filters. Figure 6 shows these gains versus the epicenter separation between the events. As expected, in no case is the S/N change significant. Thus, for distances less than 300 km, we have shown that no worthwhile S/N enhancement is gained in the match-filter output from trying to improve the waveform match by dispersing the match-filter signal either forward or backward.

The next step was to select reference event 8 as the single match filter for all the previously filtered events. This choice increased epicentral separations considerably (Table V and Figure 1). Event 8 was first used as a match filter in its original form; and the results, again expressed as S/N improvement relative to the use of closer unmodified reference events, are given in column III of Table IV. Of course the output was unchanged for those events where event 8 was previously used as the closest reference event, and so the S/N improvement is zero in these cases. These results are plotted in Figure 7. It is apparent that the use of 8 alone is overall as good a procedure as the use of closer events because there is nearly equal gain and loss in S/N ratio on the average in this plot. Figure 7 also designates the points as to which event had been previously used as the reference event in the first step. We expect some reduction in S/N as a function of increasing separation between reference event 8 and the events to be filtered; the events which had been previously filtered by event 9, 400-600 km closer to them than event 8, exemplify this even though the resultant S/N loss is not serious. Equally large S/N losses occur for events previously filtered by event 4 although event 8 is about the same epicentral distance to TFO as event 4. Here we postulate that this loss is due to large differences in spectral content as represented by the waveforms in Figure 3, with event 4 matching these filtered events better than event 8. The improvement using event 8 on events previously filtered by event 1 could be explained simply by the improved quality of the reference event itself since event 1 in Figure 3 exhibits only a fair S/N ratio compared to event 8. Events previously filtered by event 2 showed some S/N increase in the output when filtered by event 8, but it is impossible to separate real causes from the effect on the output S/N of the clipped character of event 2. Events previously filtered by event 6 show mixed results when filtered by event 8.

One further facet of interpretation is in the azimuthal differences. This does not appear to be significant over the small area studied here because where azimuthal differences were greatest (about 5° between event 8 and the events previously filtered by event 1) no decrease in S/N ratio was observed in the match-filter output.

The next step was to modify event 8 according to the dispersion curves used before and the epicentral differences between it and all the events to be filtered as given in Table V. These modified filters were applied to the events, and the results are listed in Column IV of Table IV in terms of S/N ratio gain over the use of event 8 unmodified. These results plotted in Figure 8 show that, on the average, very little is gained by this procedure -- at most 1 or 2 db for the larger distances.

One more process applied to these Pacific events was to whiten event 8 from zero to the folding frequency before match filtering all the events with it. Measurements of S/N improvement from this procedure are listed in Table IV, column V, again relative to S/N ratios obtained by using several unmodified match filters in the first step. Figure 9 illustrates the results, and it is evident the serious degradation in S/N has occurred. Thus, prewhitening the reference event over the entire spectrum, with pure noise outside the signal band, would not be prudent procedure in match filtering if S/N ratio were of paramount concern. We assume the correlation coefficients would also be degraded, thus adding error to magnitude determinations.

The last step in match filtering the Pacific events was to parameterize a chirp signal according to the formula stated previously. We can ascertain how well the chirp filter will perform by plotting the group delay time versus frequency of a signal from the Tonga Islands. It is simple to convert the group velocity measurements for the Pacific signal (Figure 5) into a plot of delay time versus frequency, as shown in Figure 10. The dispersion for the Pacific signals is clearly a poor approximation to the required linear relation. To demonstrate the poor results expected using a chirp filter on the Pacific events, we constructed a chirp filter with the following parameters:

T_0 = 36.0 sec C_0 = 4.02 km/sec

T_1 = 16.9 sec C_1 = 3.29 km/sec

An alternate shorter-period chirp signal was constructed using:

T_0 = 21.3 sec C_0 = 3.72 km/sec

T_1 = 16.3 sec C_1 = 3.10 km/sec

The linear relation between delay time and frequency for both these chirp filters is shown in Figure 10. The second one straddles that portion of the real delay-time relation where it is somewhat linear (approximately 16-22 sec period), but the real signals in this period range often have lower S/N ratio than the earlier-arriving groups. Both chirp filters were constructed to be about 500 seconds long, approximately the length of the real filters used previously; no attempt was made to find the optimum length. The results of filtering the suite of Pacific events with these chirp filters are given in Table IV, columns VI and VII, again in terms of db gain over S/N ratios obtained by several unmodified real reference waveforms (column I). Figures 11 and 12 illustrate the results for the longer-period and the shorter-period chirp, respectively. Although there is serious degradation of S/N in some cases, actually only four or five events suffered greater than a halving of the S/N ratio and the results for the whitened reference event, Figure 9, were worse. It is impossible to judge which of the two chirp filters performed better because average S/N losses appear to be about the same.

Asian events

We first match filtered the lettered events of Table II with their nearest reference event. The length of the reference signals was 1024 seconds rather than 512 seconds, as used in the Pacific analysis, since this gave better output S/N ratios in most cases. The results of this first step are listed in column I of Table VI as S/N ratios on the outputs. The next step was to modify the five reference events with the assumed Hindu Kush dispersion curve (Table III) according to the proper epicentral separations (Table VII) between reference events and the events to be filtered. The results of applying the modified filters are given in column II of Table VI in terms of db gain in output S/N over the previous step (column I); the gains are plotted in Figure 13. As expected, no significant S/N improvement is produced by the additional effort since epicentral separations are all less than 300 km.

The next step was to select event 3 as the single reference event for the entire region and apply it, unmodified, to the events previously filtered by the closer reference events.

Gains in output S/N ratios from this step are given in column III of Table VI, again relative to S/N ratios obtained by match filtering with the five closer reference events (column I). The results, plotted in Figure 14, show that, on the average, use of event 3 actually produced gains of 1 to 2 db on the output and therefore is an adequate reference event for the entire region. Checking again the Asian reference waveforms shown in Figure 4, we note that event 3 is apparently the strongest signal, especially at the longer periods; and thus we can probably attribute some of this S/N gain to use of a less noisy reference signal compared to the other four. The possibility of eliminating dispersion effects on event 3 over this source region was explored by using the Asian dispersion previously given and modifying event 3 to fit the appropriate epicentral separations as given in Table VII between event 3 and the events to be filtered. Match filtering with the modified waveforms of event 3 produced S/N gains over the use of event 3 unmodified as listed in column IV of Table VI; these are plotted in Figure 15. It is evident that the S/N gain obtained by dispersing event 3 is negligible and probably does not warrant the effort.

As in the case of the Pacific events, the single reference event was whitened from zero to folding frequency before filtering; and the results of using event 3 whitened on the Asian events are given in column V of Table VI, in S/N gain relative to column I again. The plot of these results, Figure 16, clearly shows that this procedure gives unacceptable S/N decreases in many cases. It was thought that this decrease in S/N ratio, which was also seen for the Pacific events, may result from the additional "noise" added to the spectrum outside the signal band by the whitening procedure. A better approach would perhaps be to whiten only the signal band if whitening was necessary. To test this idea, event 3 was whitened but the spectral amplitude outside the signal band (22-60 sec period, Figure 5) was everywhere set to zero to provide a band-limited filter. Column VI of Table VI gives the results of applying this type of filter to the Asian events, in S/N gain relative to column I again. The plot of these results (Figure 17) shows that S/N ratios are in general about the same as when event 3 is used undispersed and unwhitened (Figure 14); however, definite gains are apparent over Figure 16, which shows the results for the broadly-whitened spectra. We have not evaluated the effect of the band-limited filter alone, and so the effects of whitening the signal pass band and of suppressing all harmonic components outside this pass band cannot be separated; the former should decrease S/N ratios somewhat and the latter improve them. Comparison of Figure 17 with Figure 14 reveals that these effects do tend to cancel each other. We expect that results would have been similar if we had tried a band-limited, whitened filter on the Pacific events.

The next step involved parameterization of a chirp filter, as described above, appropriate to the Asian signals recorded at TFO. The following parameters were chosen:

$$T_0 = 60.0 \text{ sec} \qquad C_0 = 3.84 \text{ km/sec}$$
$$T_1 = 22.0 \text{ sec} \qquad C_1 = 2.93 \text{ km/sec}$$

The length of this filter is between 950 and 1000 secs, depending on epicentral distance, only slightly shorter than the

1024-second real signals used in this Asian analysis. The linear relation between relative delay time and frequency for this filter closely approximates the observed relation from a Hindu Kush Rayleigh wave as shown in Figure 10. Results of using this chirp filter are listed in column VII of Table VI and illustrated in Figure 18, again in terms of db gain relative to the output of step one (column I). It appears that the chirp filter, on the average, works as well as the real reference event in this source region and should be regarded as a safe alternative to using real waveforms.

Finally, we experimented with a synthetic match filter constructed from the "Shield" phase velocities of Brune (1969). Figure 5 shows that the group velocity dispersion of this structure is not greatly different from the empirical curve for the Asian signal. This experiment was made to simulate a circumstance where a match filter was required and no previous signal from the source area of interest had been recorded but there was some knowledge of the structure along the path. The program was set up to construct these synthetic filters with a white spectrum so that results are biased by the bad effect of a fully whitened spectrum as seen in Figure 16. The program was capable of constructing the synthetic signal for the distance of each event to be filtered so that dispersion effects due to differences in epicentral distance do not arise. The results, in S/N gain over the base data again, are given in Table VI under column VIII and plotted in Figure 19. Allowing about a -2 db shift in the zero line due to full-spectrum whitening, the synthetic filter results indicate that it too will provide adequate match filtering for the Asian events. This experiment was not tried for the Pacific events; for with those the shape of the group velocity curve is critical, and this shape can be perturbed significantly by the depth of the water layer in an assumed oceanic structure. Thus we would expect that results with synthetic match filters on the Pacific events would show S/N decrease relative to real filters, perhaps very large S/N decrease, unless the structure of the propagation path were well known.

CONCLUSIONS

It has been shown in match filtering two suites of events, one from the Tonga Islands region and another from the Hindu Kush region, that the proximity of a reference event to an event to be filtered is not of importance -- at least to distances of 600 km -- since for both suites a single reference event gave as good output S/N ratios, on the average, as several evenly distributed reference events over a source area almost 1000 km across. It should be remembered that the single reference events chosen had S/N ratios as high or higher than the several other reference events, and thus performance on their part may be due somewhat to improved S/N ratio. We then conclude that a distant, high S/N event may be as good or better than a close, low S/N event for detection purposes. We urge caution in extending this conclusion to other source areas, however.

Dispersion curves assumed to be appropriate to the two source regions were used to modify the reference events by dispersing them forward or backward to remove the dispersion effects over the epicentral separation distance, up to 600 km in some cases. Application of these dispersion-corrected waveforms results in S/N gain, on the average, of about 1 db, and this is probably not sufficient to encourage routine use of this modification procedure, at least below the 600 km separation. The fact that the sample was not large and that in many cases db losses were observed combined to further degrade the potential of this procedure, at least for the distances considered here (600 km or less). This result is in agreement with demonstrations of small decreases in correlation coefficients using synthtetic seismograms at various distances (Alexander and Rabenstine, 1967).

Prewhitening the reference waveforms before match-filtering will not significantly degrade the S/N ratio on the match-filter output provided the whitening is done only in the signal band. Whitening the entire spectrum resulted in significant S/N losses, over 6 db in a few cases.

Chirp waveforms perform as well as real signals when the waves traverse structures which give a nearly linear relation between Rayleigh-wave group delay time and frequency, such as Hindu Kush to TFO. This point was also made by Capon et al. (1969) in regard to Kazahk events. In contrast, when group delay time is not a linear function of frequency for a certain path, such as Tonga Islands to TFO, the chirp filter performs poorly, as predicted. In practice, then, the efficacy of a chirp waveform relative to a real signal could be judged *a priori* if at least one event from the area of interest were recorded so that the group delay time versus frequency could be plotted. Certainly the parameters of the chirp waveform must change from area to area. If no signal were available from an area of interest, assumed dispersion curves could provide a plot of group delay time versus frequency by which to judge the value of a chirp-waveform match-filtering scheme; or the assumed dispersion curve could be used to construct a synthetic filter, which was shown to perform as well as real or chirp filters on the Asian events of this study.

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TABLE I

Pacific Events Used in This Study

Code	Date	Origin Time	Depth	m_b	Distance*	Azimuth*
T	10 Jan 67	13 34 06	33	5.0	9055	239
V	03 Feb 67	02 56 00	70	4.6	9103	238
Q	14 Feb 67	18 13 14	33	4.9	8805	238
CD	19 Feb 67	14 21 53	33	4.4	9138	237
EF	23 Feb 67	05 58 29	21	4.8	9092	237
LM	24 Feb 67	05 14 08	33	4.7	9338	236
R	12 Mar 67	00 53 06	66	4.4	8948	239
A	22 Mar 67	23 46 21	33	4.7	8809	244
H	29 Mar 67	19 53 58	33	4.7	8503	241
E	16 Apr 67	02 23 05	33	4.5	8522	241
G	29 Apr 67	12 31 09	59	4.6	8605	241
U	04 May 67	10 18 58	33	4.9	9094	240
W	07 Jun 67	09 57 59	33	4.3	9064	238
J	22 Jun 67	10 50 05	33	4.5	8531	240
D	28 Jun 67	05 34 06	40	4.8	8420	241
Z	29 Jun 67	10 36 29	33	4.4	9062	237
PQ	02 Sep 67	03 10 56	65	4.3	9383	236
AB	10 Nov 67	03 27 34	100	4.8	9185	238
F	20 Nov 67	02 11 25	33	4.8	8624	242
M	23 Dec 67	00 56 53	38	4.3	8652	240
C	09 Jan 68	09 26 14	75	4.7	8628	242
S	15 Jan 68	05 43 09	33	4.6	9007	239
GH	19 Feb 68	09 50 07	46	4.7	9342	237
B	09 Mar 68	20 59 41	42	4.7	8663	243
X	24 Oct 69	22 30 58	33	5.3	8887	237
P	28 Jan 70	19 38 37	33	4.5	8730	238
6	21 Mar 67	11 24 45	33	5.4	9315	236
8	05 Jun 67	01 21 20	33	5.2	9077	237
9	16 Nov 67	01 33 56	33	4.2	8555	242
1	06 Oct 68	08 47 02	35	5.4	8686	243
2	29 Jan 69	17 44 31	33	6.0	8548	239
4	21 Jul 69	02 22 06	33	4.8	9082	240

*In kilometers and degrees from TFO

TABLE II

Asian Events Used in This Study

Code	Date	Origin Time	Depth	m_b	Distance*	Azimuth*
A	04 Jun 64	02 57 08	33	4.9	12,197	360
B	24 Oct 64	06 51 02	57	5.1	11,928	358
C	11 Jan 66	09 12 59	40	5.4	12,456	357
D	28 Jan 66	08 52 02	20	5.4	11,863	356
F	19 Feb 66	12 50 42	59	5.1	12,316	358
LM	06 Apr 66	01 51 52	38	5.1	12,340	356
G	15 May 66	02 13 03	51	4.9	11,823	356
H	01 Oct 66	07 38 29	25	5.3	12,371	358
J	06 Dec 66	02 30 53	58	4.9	12,218	359
K	11 Feb 67	08 05 08	58	4.6	12,160	358
L	12 Feb 67	16 06 48	100	5.2	12,260	358
P	08 Sep 67	05 23 41	14	4.9	11,973	359
R	17 Apr 68	09 50 39	94	4.8	12,204	358
JK	19 Oct 68	09 52 03	33	5.4	12,061	356
V	01 Nov 68	20 49 17	41	4.7	12,056	357
X	13 May 69	10 04 39	33	4.8	11,806	358
Y	29 Jun 69	03 40 13	39	5.1	11,644	354
Z	26 Aug 69	03 23 19	65	4.7	12,109	357
AB	21 Sep 69	19 09 54	72	4.7	12,242	359
EF	29 Dec 69	18 08 56	42	4.7	12,124	357
2	10 Aug 66	22 05 35	4	5.5	11,975	359
3	05 Jan 67	10 07 58	11	5.3	11,853	357
4	03 Mar 68	09 31 20	33	5.2	12,377	357
1	27 Jan 69	10 59 27	49	5.2	12,092	358
5	27 Mar 69	11 19 29	37	4.9	11,902	357

*In kilometers and degrees from TFO

TABLE III

Assumed Dispersion Curves for Hindu Kush
and Tonga Island Regions

Tonga Islands

T(sec)	C($\frac{km}{sec}$)
100	4.0
45	4.0
35	3.9
25	3.8
20	3.7
15	3.6

Hindu Kush

T(sec)	C($\frac{km}{sec}$)
100	4.1
45	4.0
35	3.9
25	3.7
20	3.5
15	3.3

TABLE IV

Match-Filter Results for Pacific Events

Event	I	II	III	IV	V	VI	VII
	S/N	db	db	db	db	db	db
AB	5.05	-.17	0	- .17	- .07	-1.24	-8.48
V	2.25	-.08	0	- .08	.00	- .89	.26
CD	15.51	.17	0	.17	-5.10	-6.20	- .53
W	11.21	.04	0	.04	-5.07	-3.66	-4.99
EF	8.03	.02	0	.02	-5.46	3.12	-1.55
Z	7.13	.00	0	.00	-6.35	.08	-4.41
X	10.17	-.31	0	- .31	-6.15	-2.30	-4.52
GH	4.57	.08	-2.22	1.24	- .90	-3.74	-11.60
LM	5.03	-.12	.20	.14	-6.75	- .93	.58
PQ	7.61	.01	2.20	.93	-2.03	-1.21	- .16
H	20.86	-.02	-1.24	1.10	-8.10	-5.18	-4.15
E	11.91	-.04	- .20	.65	-3.80	-1.70	-2.61
G	9.73	-.17	-2.88	- .08	-2.29	-4.54	-8.73
J	10.82	-.07	- .38	.98	-3.36	-2.16	-4.96
F	50.09	-.11	-2.98	1.87	-7.60	-5.56	-3.61
D	9.72	-.26	-3.80	1.72	-5.84	-2.63	-1.77
A	21.66	.10	2.46	- .07	.54	.74	-1.59
B	28.08	.06	1.26	1.04	- .08	.45	-1.72
C	18.88	.03	4.86	.32	-2.38	4.43	1.91
Q	4.62	-.46	4.00	.03	-7.01	1.82	3.71
M	2.50	-.03	2.08	.94	1.67	2.01	-4.97
P	5.46	-.44	.81	1.25	-1.97	- .73	-2.83
U	25.30	-.01	-4.04	- .01	-5.39	-7.51	-1.42
S	3.09	.08	- .72	-2.27	- .82	-4.22	-6.93
T	29.60	-.10	-4.08	.09	-4.98	-6.26	-8.34
R	3.75	-.21	-4.16	.07	-2.54	-2.92	-3.45

I - Output S/N ratio of events filtered by the close reference events

II - Gain over I when close reference events are dispersed

III - Gain over I when events are filtered by event 8

IV - Gain over III when event 8 is dispersed

V - Gain over I when event 8 is dispersed and whitened

VI - Gain over I when longer-period chirp is used

VII - Gain over I when shorter-period chirp is used

TABLE V

Epicentral-Distance Differences for Pacific Events

Reference Event	Δ_R km	Filtered Event	Δ_F km	$\Delta_F-\Delta_R$ km	$\Delta_F-\Delta_{R_8}$ km
8	9077	AB	9185	108	108
		V	9103	26	26
		CD	9138	61	61
		W	9064	- 13	- 13
		EF	9092	15	15
		Z	9062	- 15	- 15
		X	8887	-190	-190
6	9315	GH	9342	27	265
		LM	9338	23	261
		PQ	9383	68	306
9	8555	H	8503	- 52	-574
		E	8522	- 33	-555
		G	8605	50	-472
		J	8531	- 24	-546
		F	8623	68	-454
		D	8420	-135	-657
1	8686	A	8809	123	-268
		B	8663	- 23	-414
		C	8628	- 58	-449
2	8547	Q	8805	258	-272
		M	8652	105	-425
		P	8730	183	-347
4	9082	U	9094	12	17
		S	9007	- 75	- 70
		T	9005	- 27	- 22
		R	8948	-134	-129

TABLE VI

Match-Filter Results for Asian Events

Event	I	II	III	IV	V	VI	VII	VIII
	S/N	db	db	db	db	db	db	db
G	6.30	.02	0	.03	-5.40	- .39	- .44	-2.94
Y	5.36	.71	0	.71	.03	2.14	1.31	.08
D	9.99	- .03	0	- .03	-3.11	2.46	.16	-4.06
K	4.44	- .27	-3.10	.15	-4.33	-2.90	-1.99	-4.68
Z	5.11	- .17	2.24	- .05	-1.74	1.68	.75	.73
R	6.00	.10	.76	.47	- .63	1.87	- .41	-3.76
JK	10.40	- .01	2.66	.09	1.18	.86	.42	-1.78
EF	2.71	.16	1.60	- .29	-2.99	- .32	-1.16	-1.50
X	6.10	- .14	1.62	.22	.51	2.09	2.04	- .93
B	6.47	.03	3.96	- .07	1.29	3.72	5.08	1.94
C	4.32	- .08	2.12	- .70	.72	2.19	3.34	-1.49
F	11.97	- .19	.60	.54	- .44	- .79	-2.86	- .42
H	9.09	- .01	2.60	.88	2.30	3.77	-1.03	2.42
L	7.07	- .09	.12	-1.06	-4.04	2.50	2.65	- .14
LM	23.40	- .04	-2.04	.50	-2.86	-1.49	-2.23	-2.01
U	2.76	.84	.40	.75	-3.15	.52	-2.97	-3.95
J	3.54	- .50	- .78	- .40	-1.26	.50	-1.44	-2.65
AB	4.72	.09	-2.16	.30	-3.40	-1.86	- .45	-2.57
P	3.61	.00	3.72	- .10	2.94	3.12	4.16	4.12
A	5.06	.17	2.30	1.39	.35	1.23	1.64	- .14

I - Output S/N ratio of events filtered by the close reference events

II - Gain over I when close reference events are dispersed

III - Gain over I when events are filtered by event 3

IV - Gain over III when event 3 is dispersed

V - Gain over I when event 3 is dispersed and whitened

VI - Gain over I when event 3 is dispersed and band-pass whitened

VII - Gain over I when chirp is used

VIII - Gain over I when synthetic filter (whitened) is used

TABLE VII

Epicentral Distance-Differences for Asian Events

Reference Event	Δ_R km	Filtered Event	Δ_F km	$\Delta_F-\Delta_R$ km	$\Delta_F-\Delta_{R3}$ km
3	11853	G	11823	- 30	- 30
		Y	11644	-209	-209
		D	11863	10	10
1	12092	K	12160	68	307
		Z	12109	17	256
		R	12204	112	351
		JK	12061	- 31	208
		EF	12124	32	271
5	11902	X	11806	- 96	- 47
		B	11928	26	75
4	12377	C	12456	79	603
		F	12316	- 61	463
		H	12371	- 6	518
		L	12260	-117	407
		LM	12340	- 37	487
2	11975	U	12108	133	255
		J	12218	243	365
		AB	12242	267	389
		P	11973	- 2	120
		A	12197	222	344

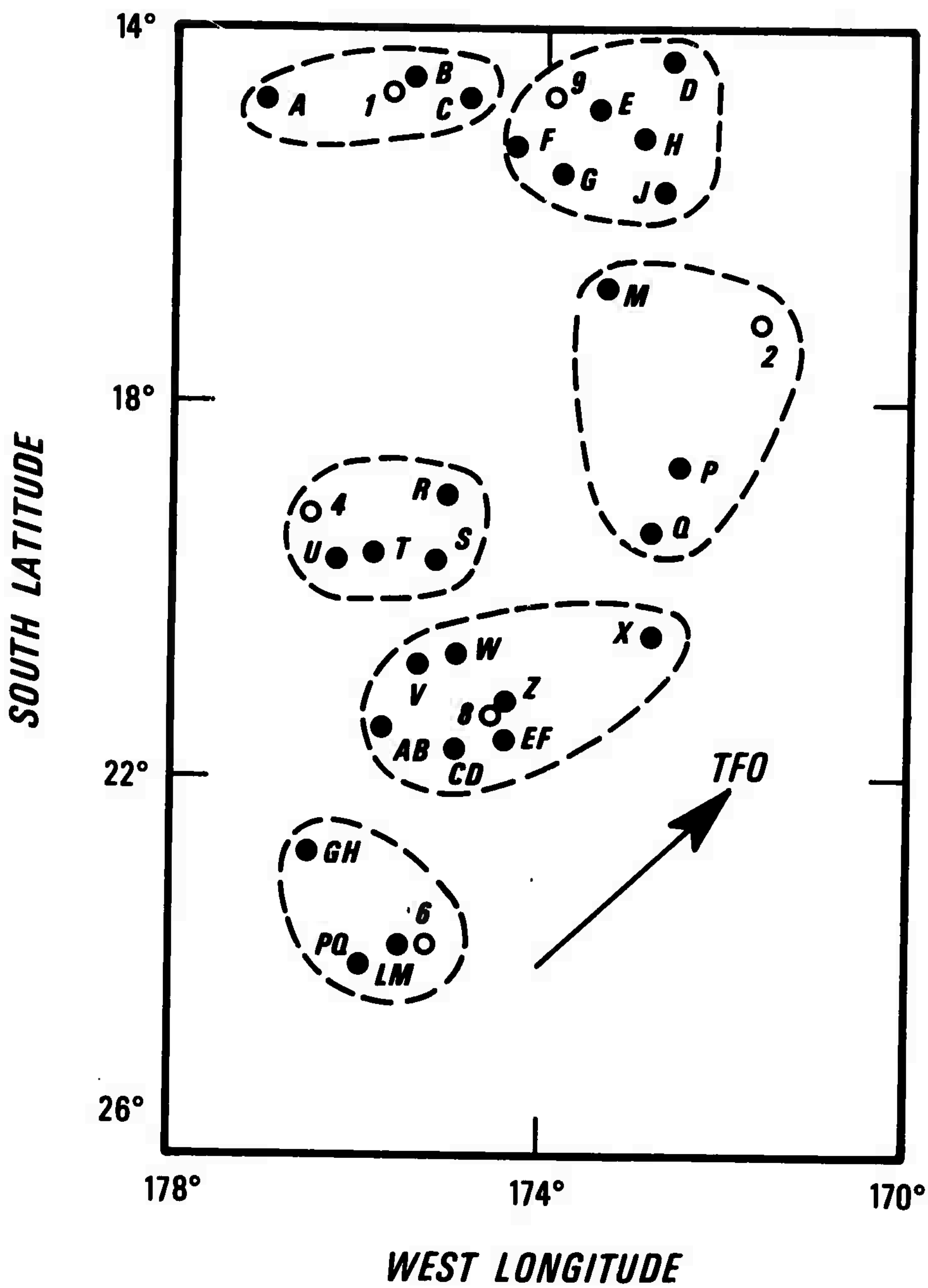

Figure 1. Location of Pacific events.

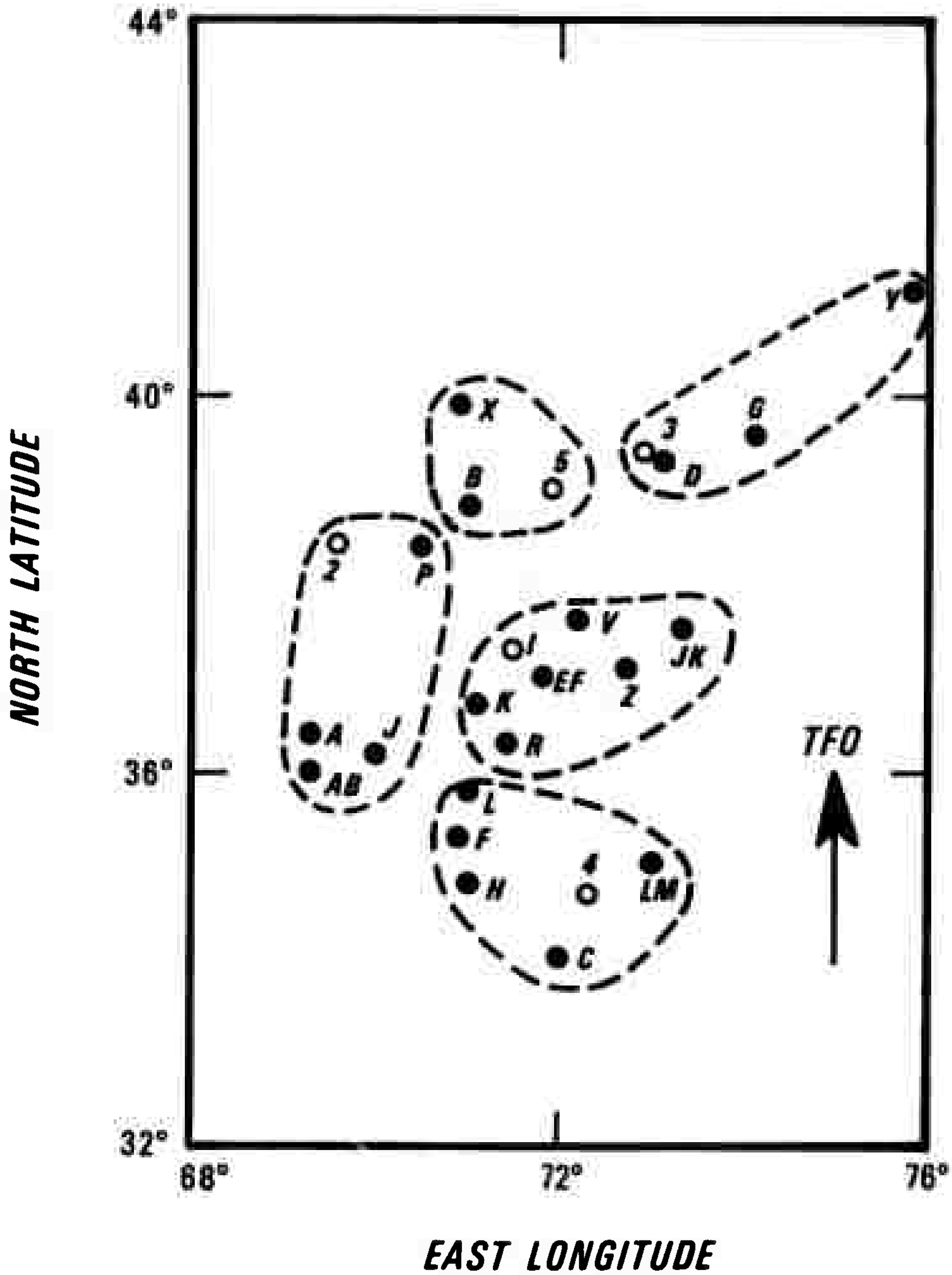

Figure 2. Location of Asian events.

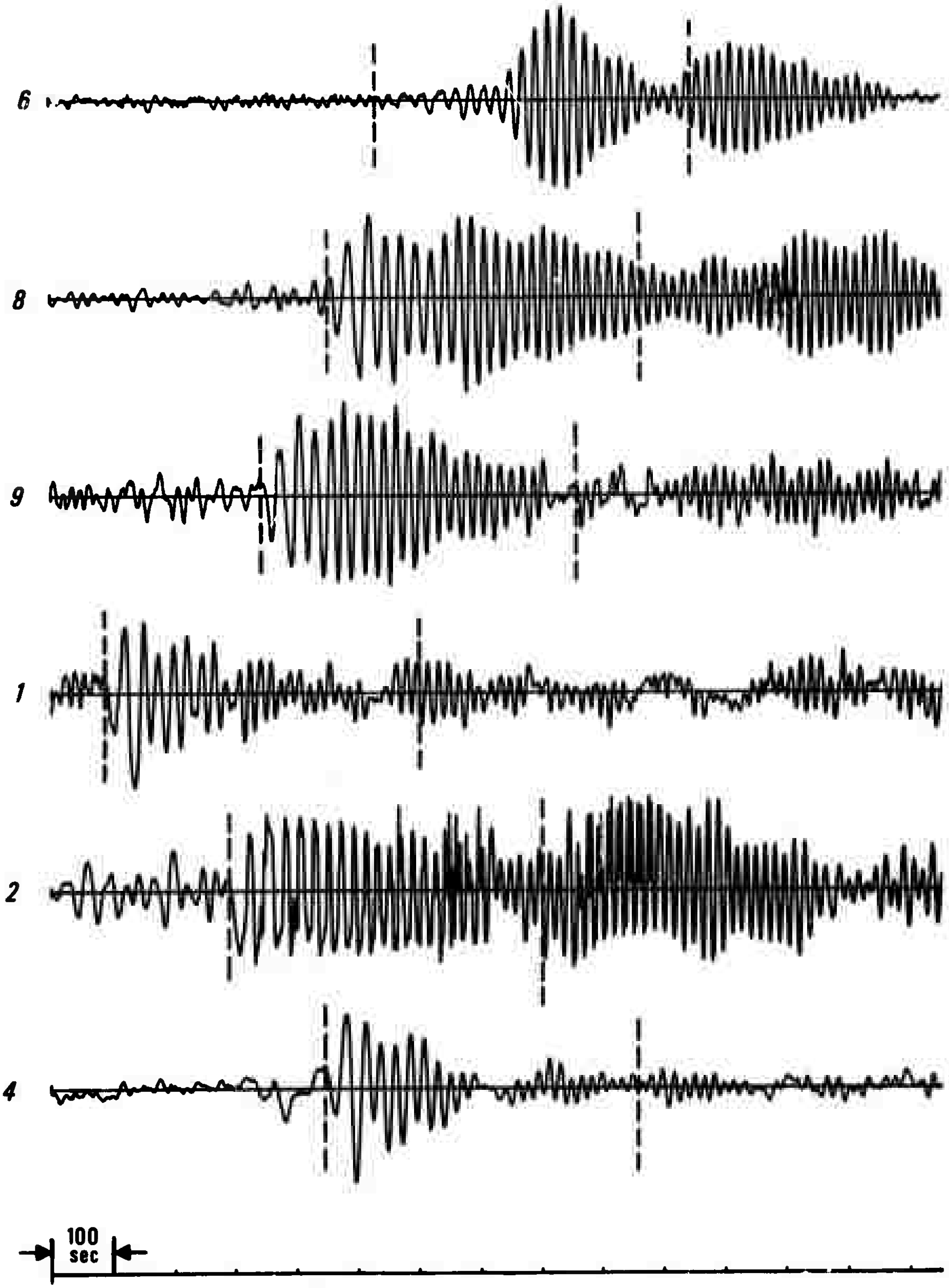

Figure 3. Reference event waveforms from Pacific events.

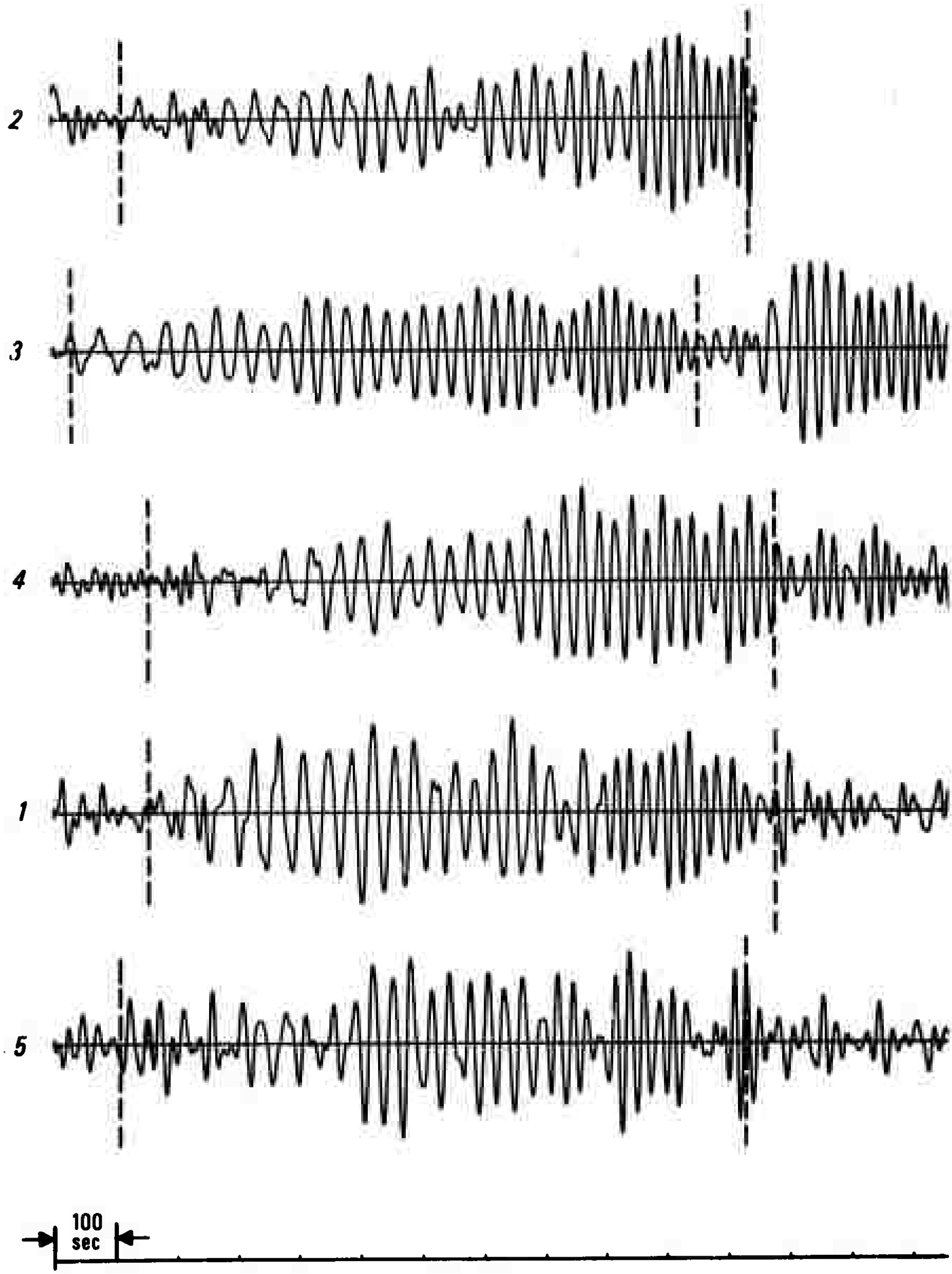

Figure 4. Reference event waveforms from Asian events.

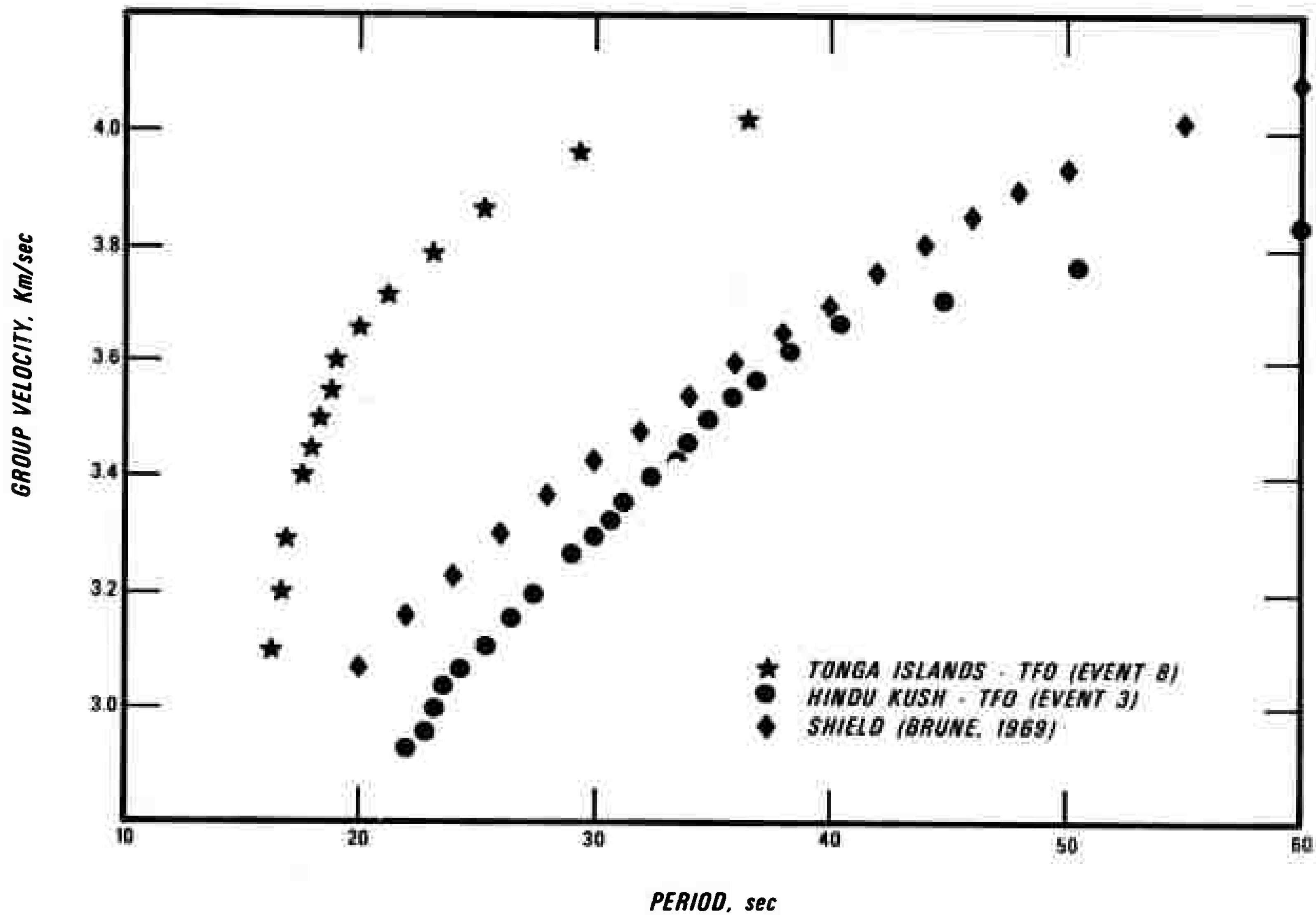

Figure 5. Group velocity dispersion for Pacific and Asian source regions to TFO.

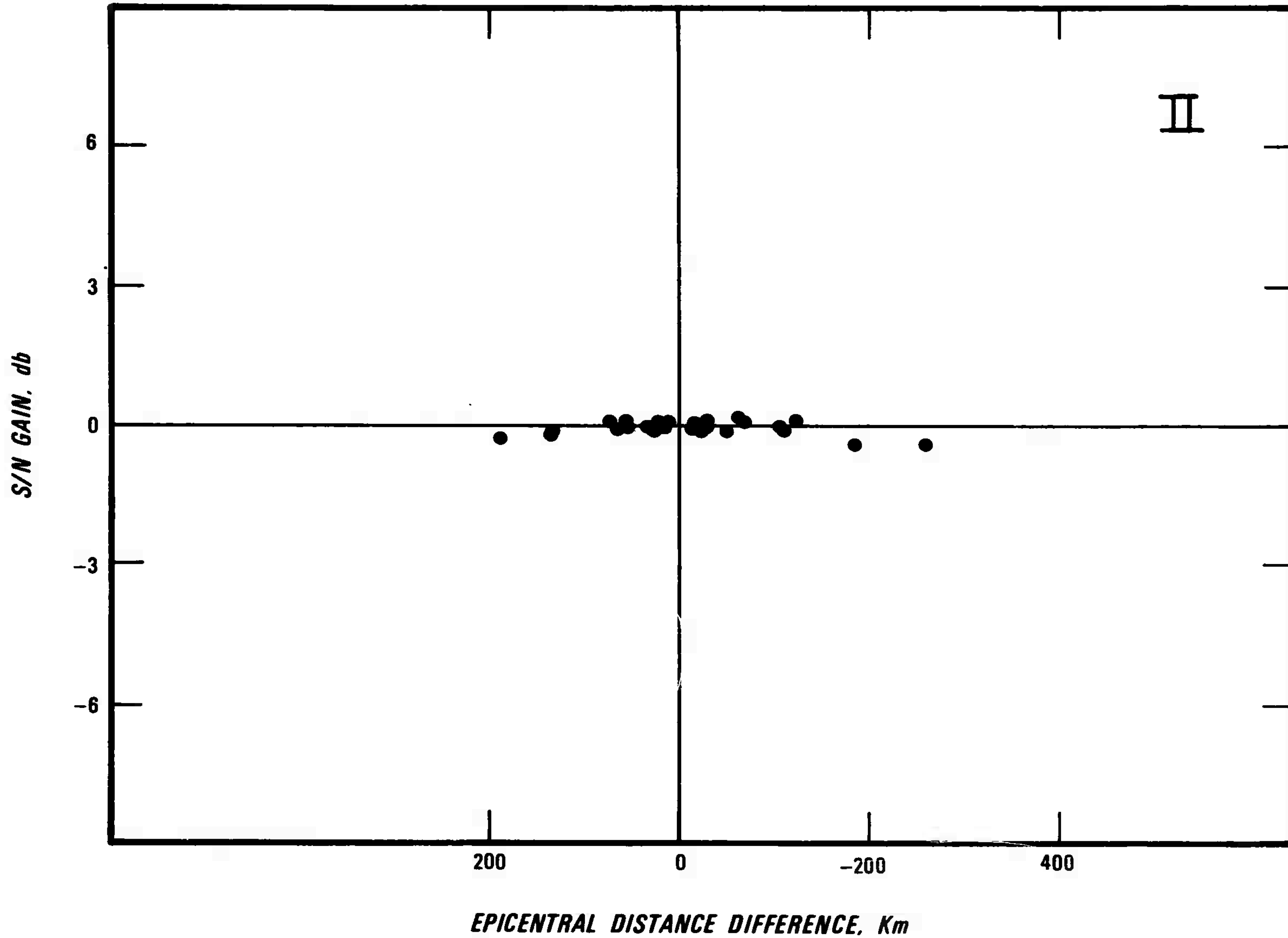

Figure 6. Gain in S/N achieved by dispersing the six Pacific reference events to fit the distances of the events to be filtered.

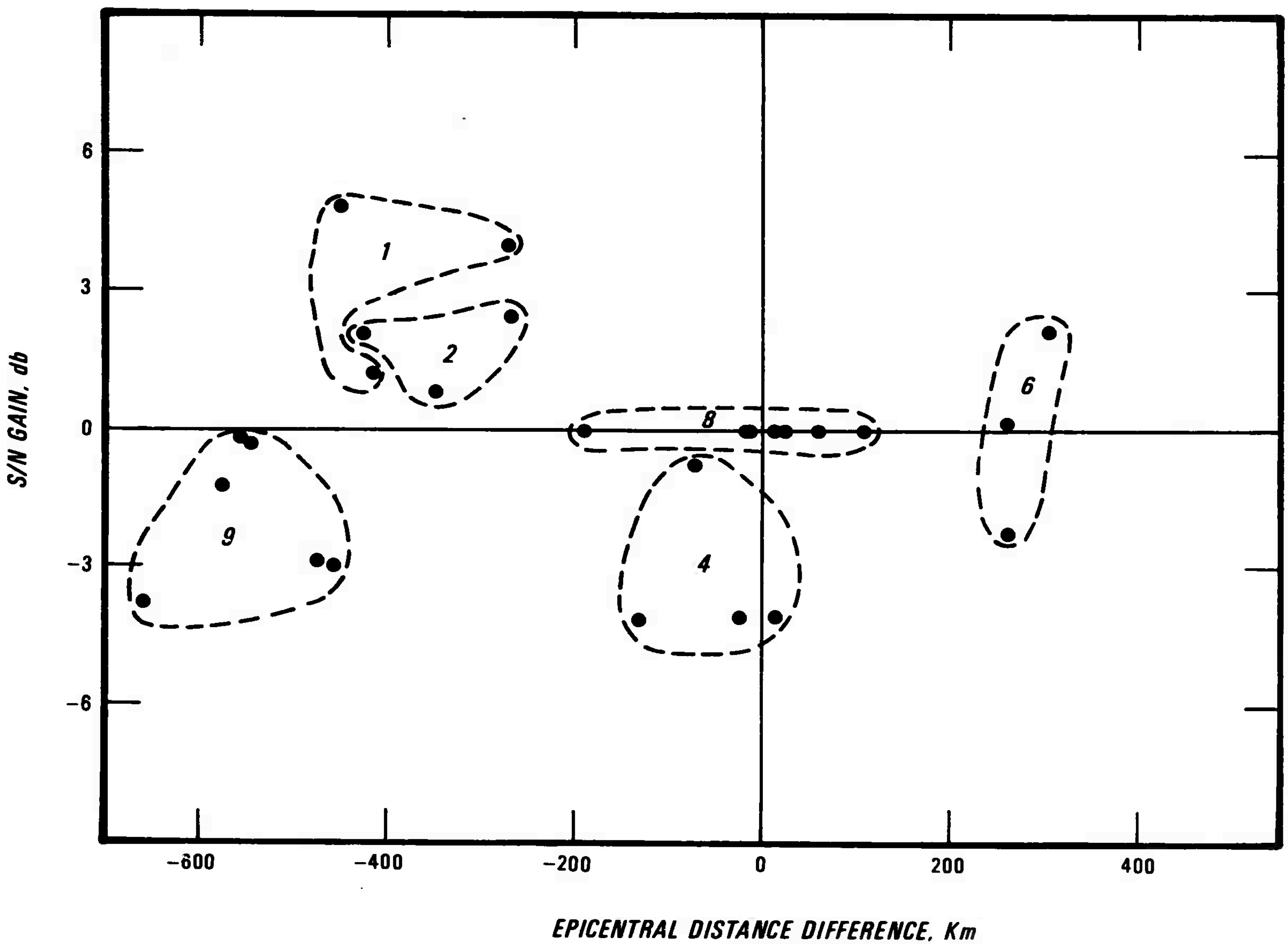

Figure 7. Gain in S/N achieved by using one event (8) rather than six separate ones in the Pacific.

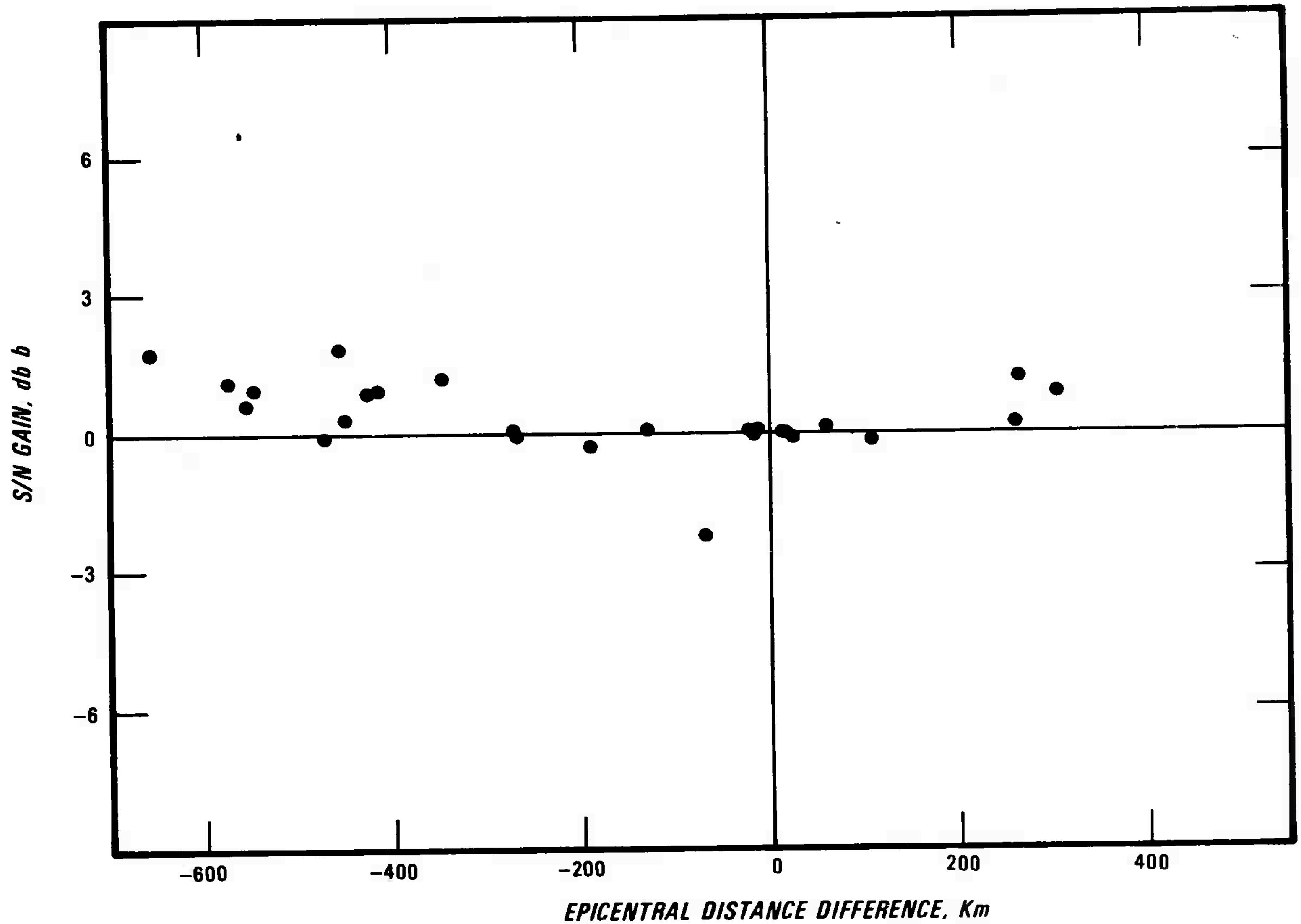

Figure 8. Gain in S/N achieved by dispersing Pacific event 8 to fit the distances of the events to be filtered.

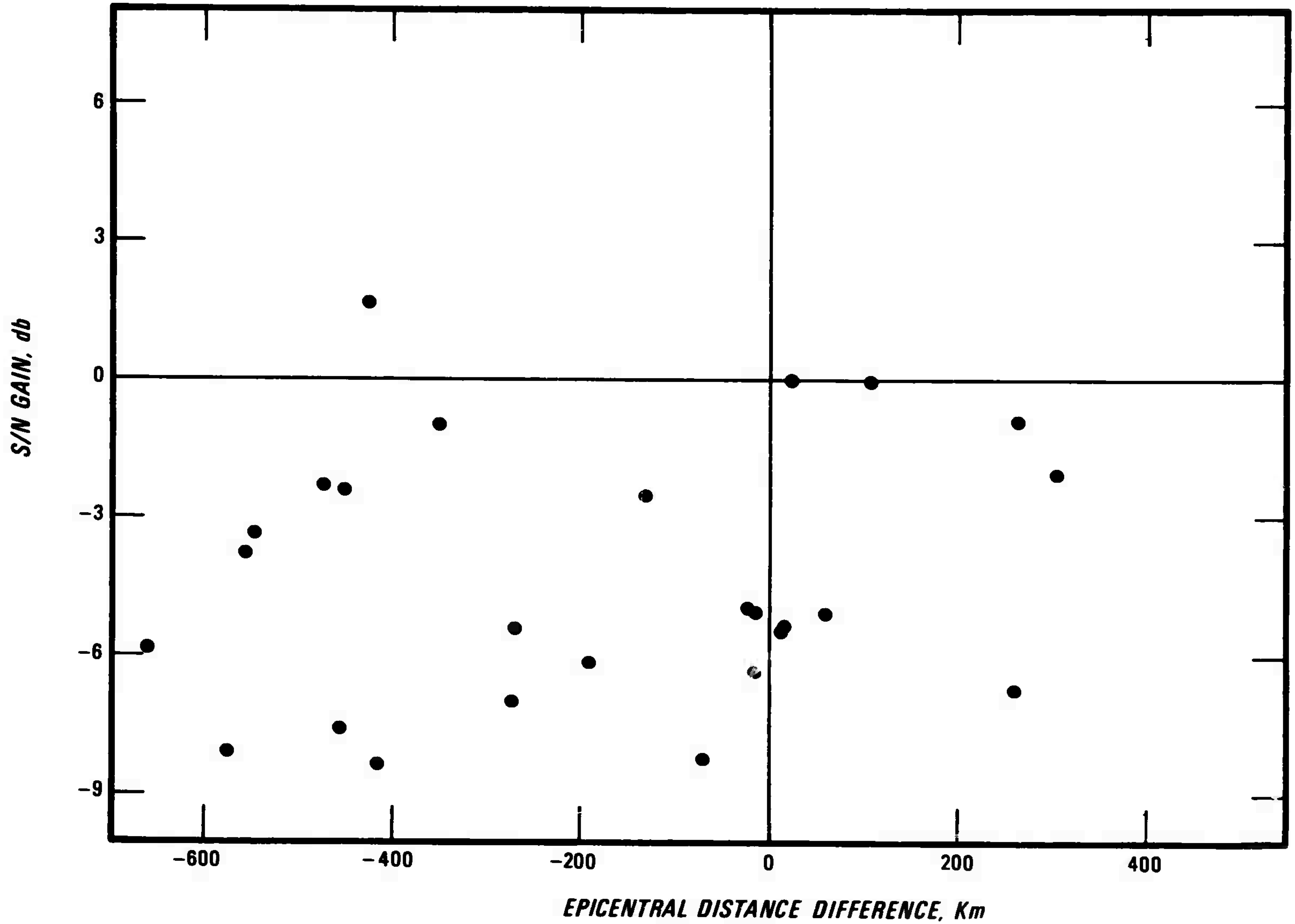

Figure 9. Gain in S/N achieved by whitening event 8 before filtering the Pacific events.

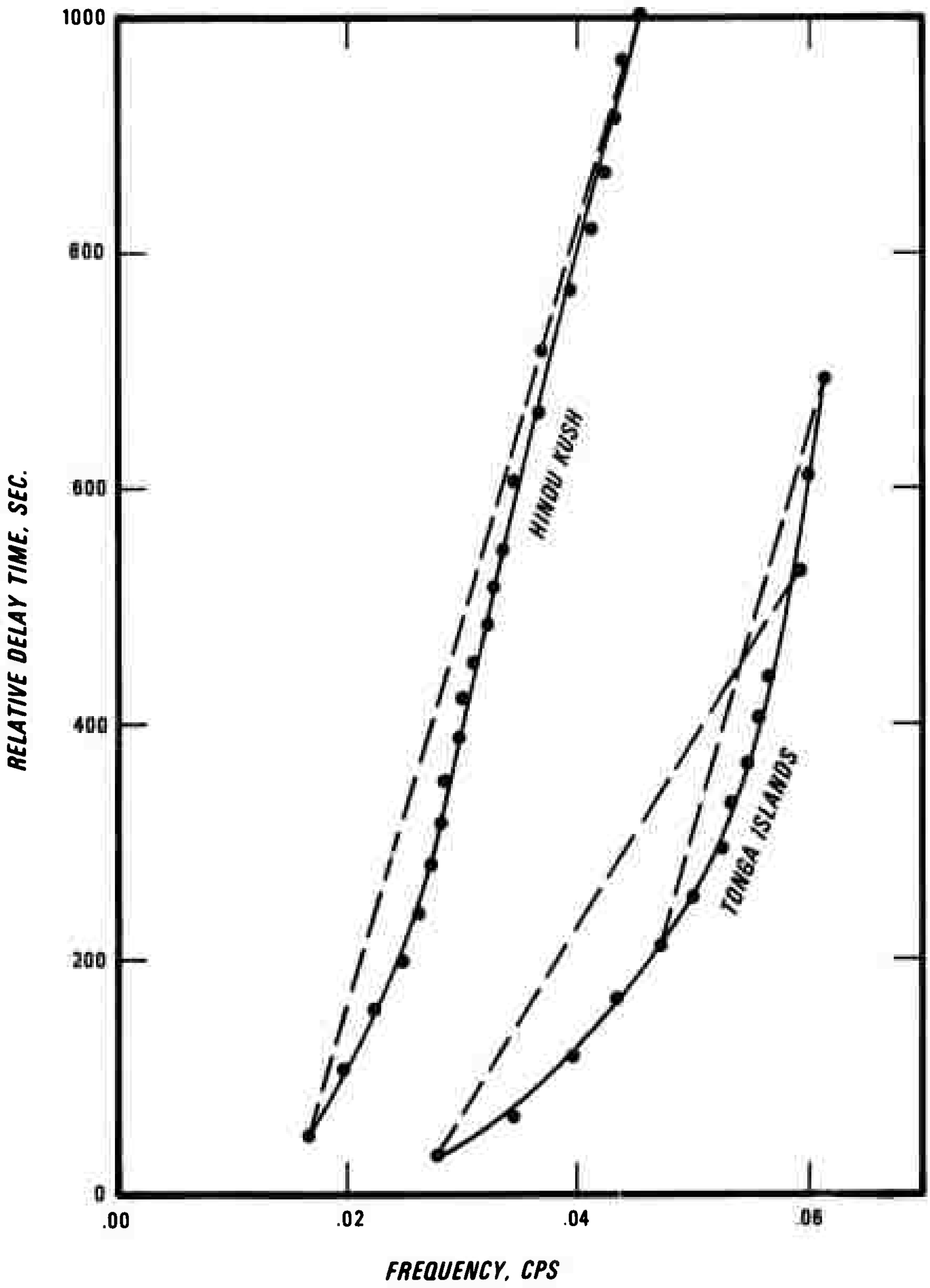

Figure 10. Relative delay times versus frequency for Rayleigh waves from the Hindu Kush and the Tonga Islands to TFO.

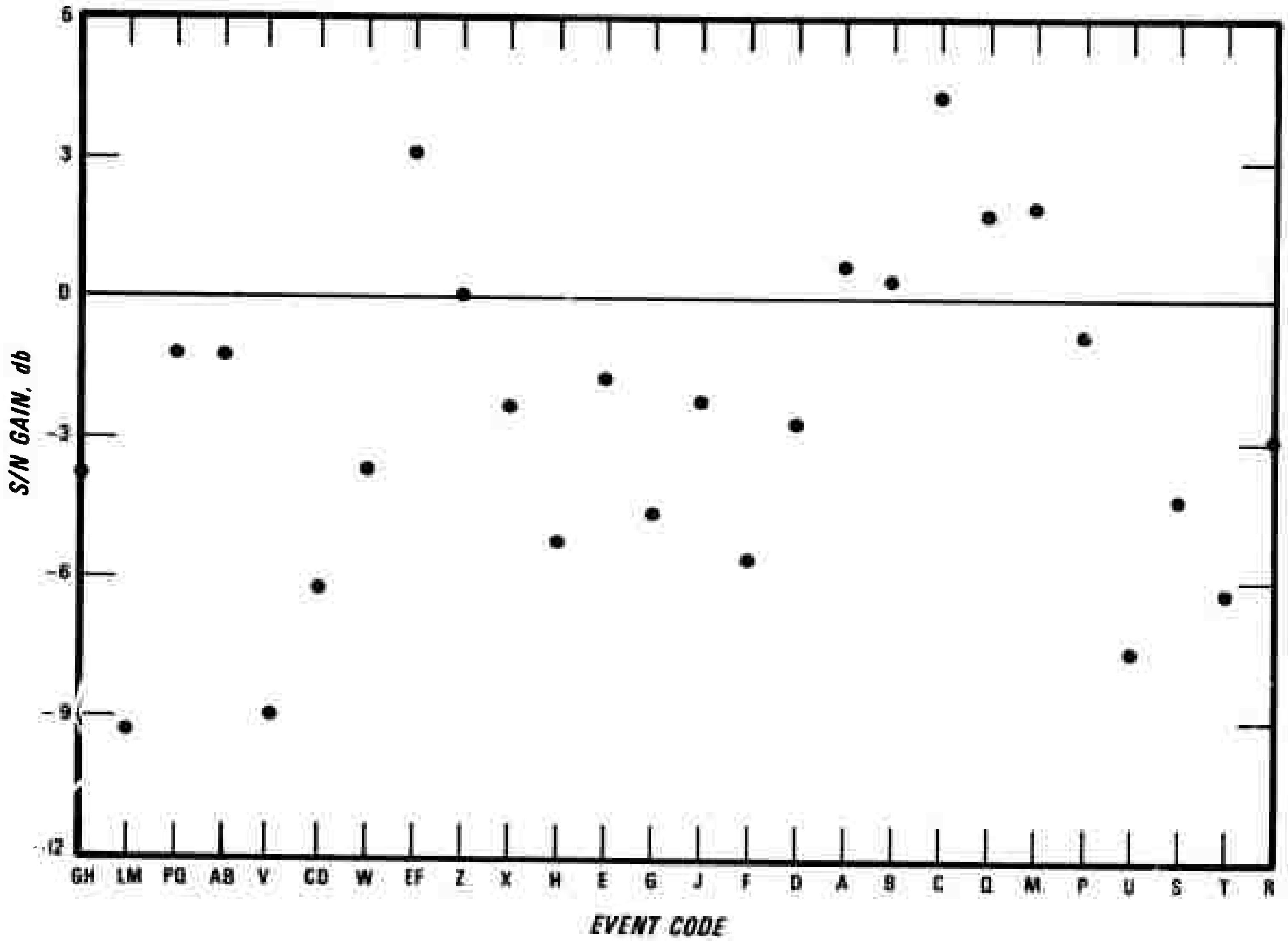

Figure 11. Gain in S/N achieved by using a chirp (36-17 sec) waveform rather than six real signals in match filtering the Pacific events.

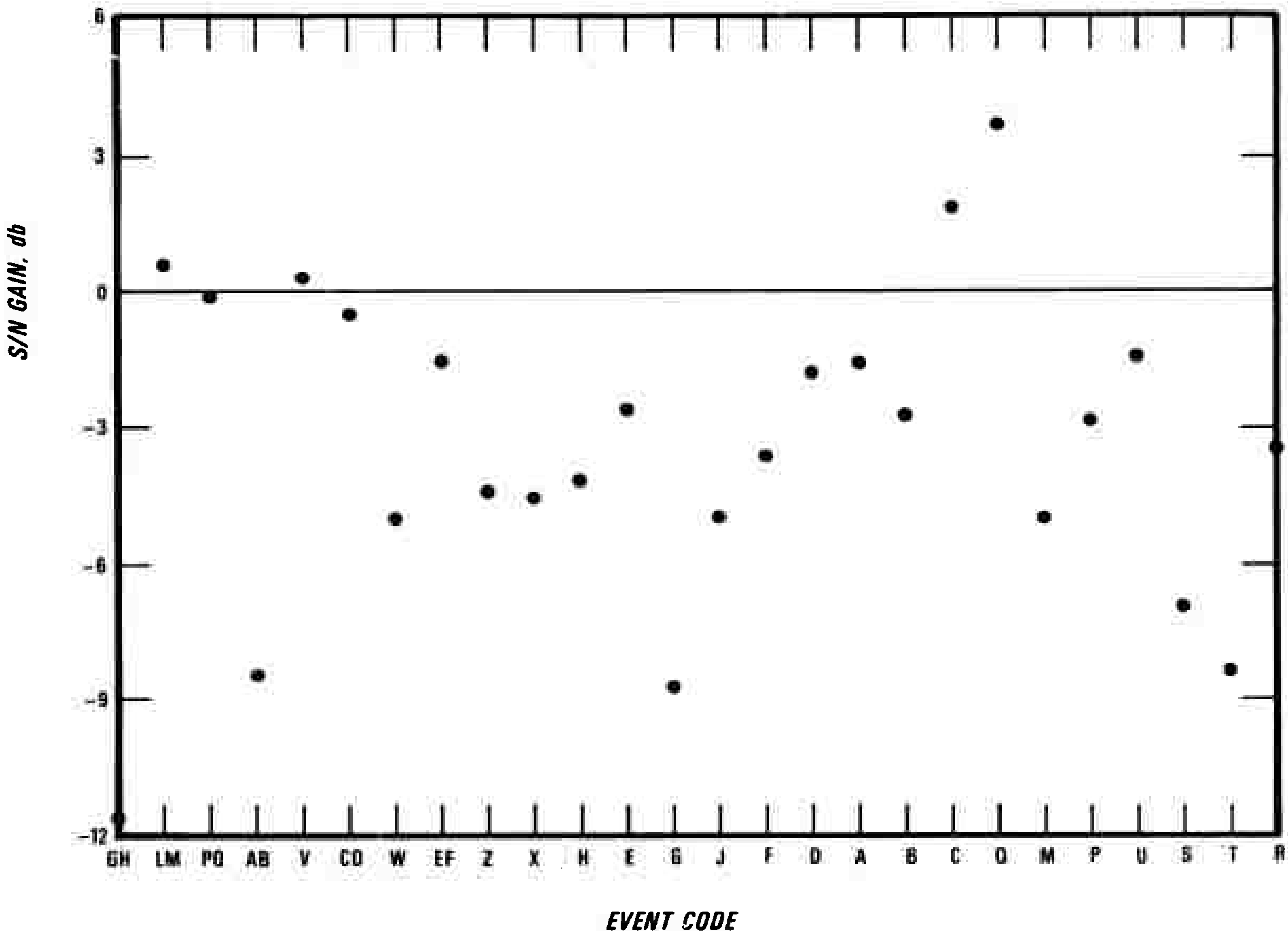

Figure 12. Gain in S/N achieved by using a chirp (21-16 sec) waveform rather than six real signals in match filtering the Pacific events.

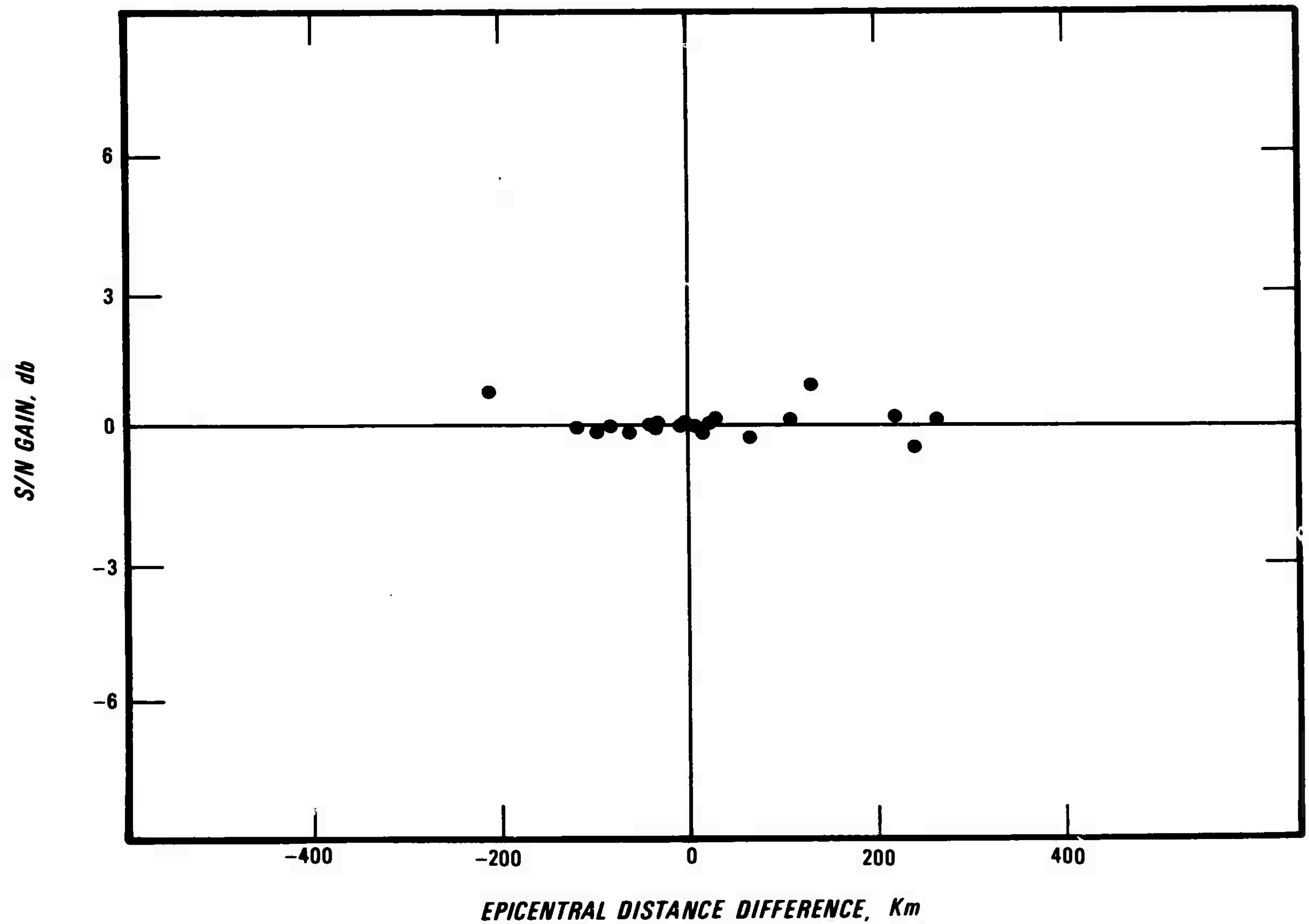

Figure 13. Gain in S/N achieved by dispersing the five Asian reference events to fit the distances of the events to be filtered.

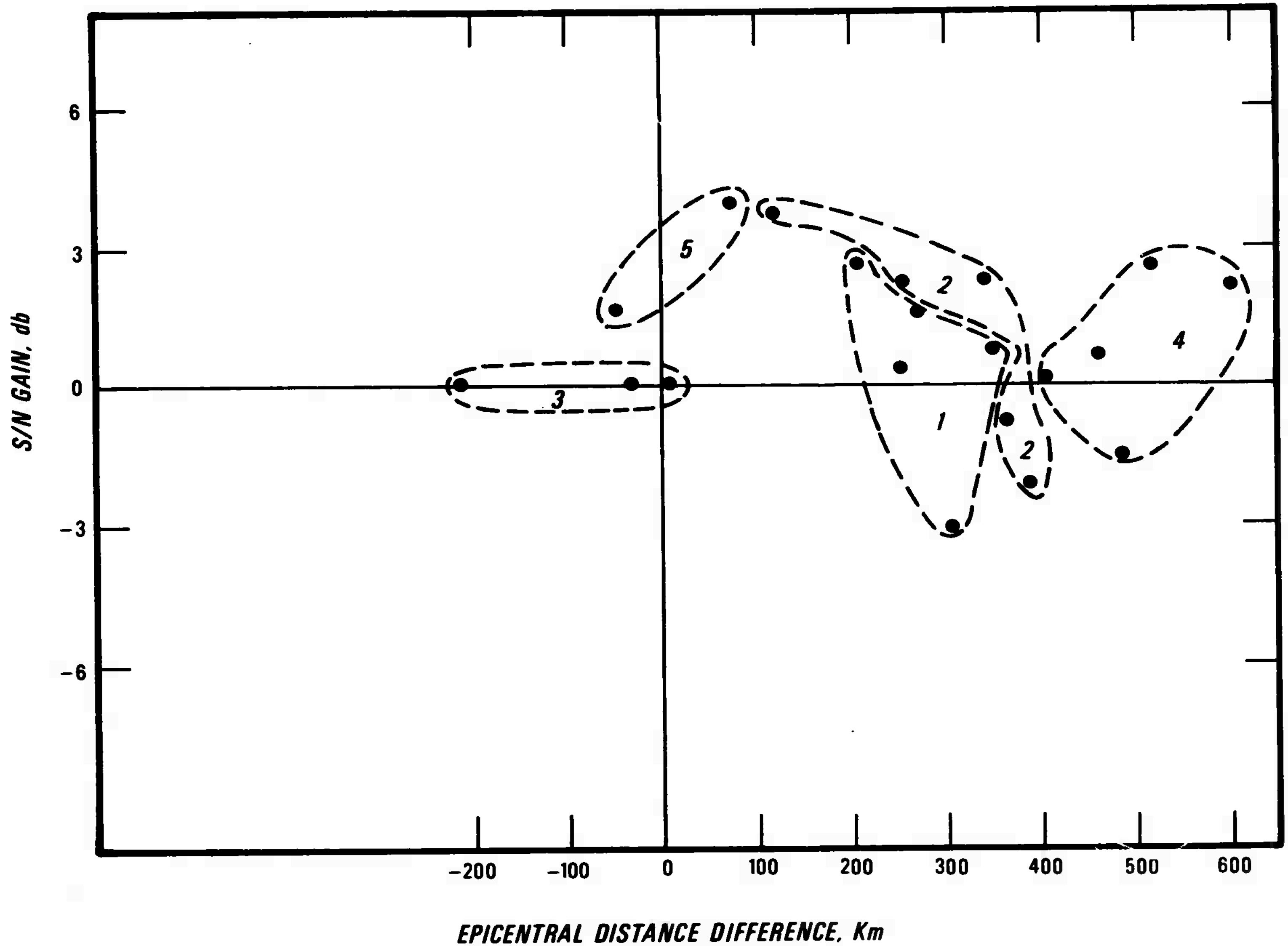

Figure 14. Gain in S/N achieved by using one event (3) rather than five separate ones in Asia.

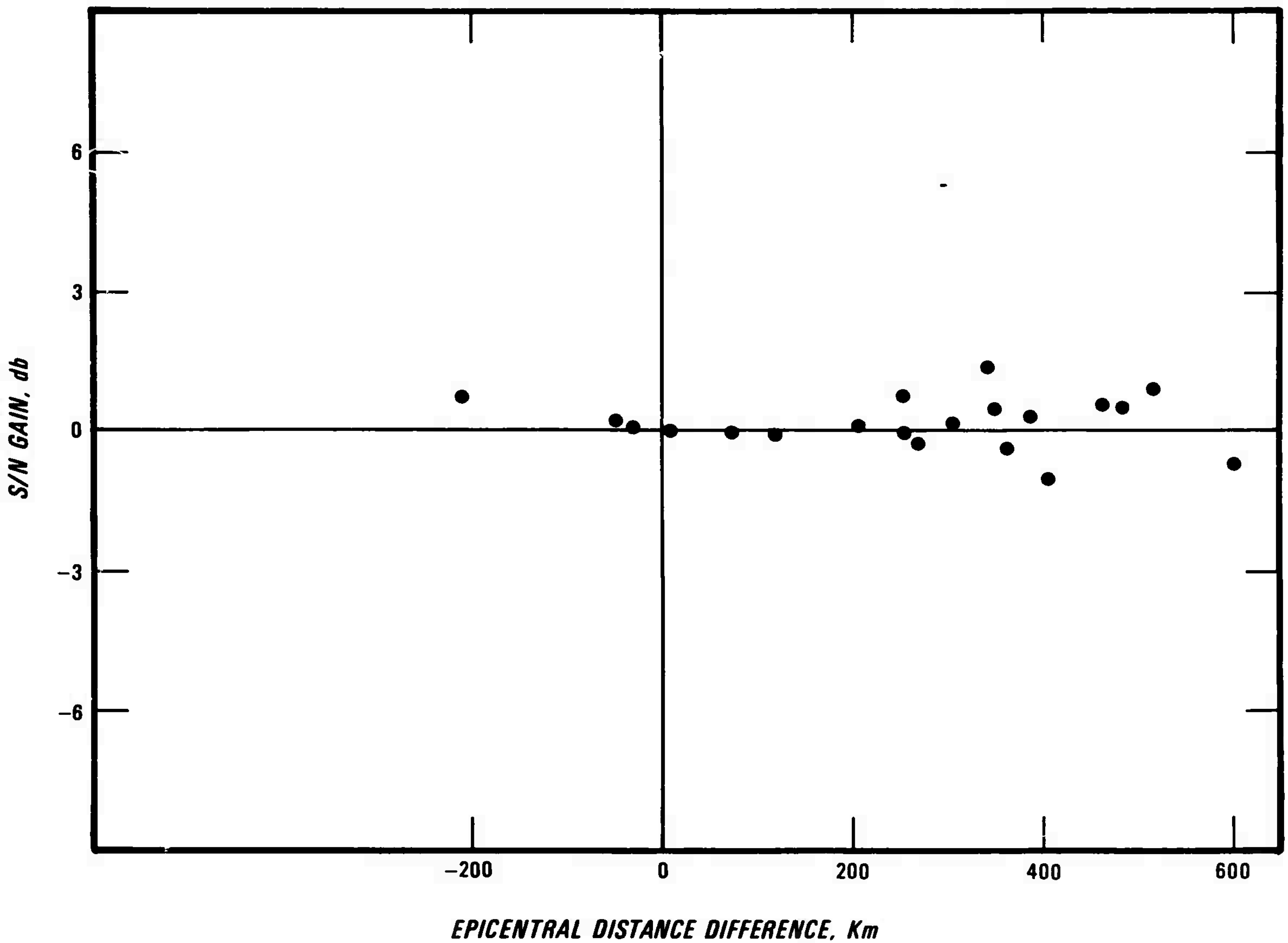

Figure 15. Gain in S/N achieved by dispersing Asian event 3 to fit the distances of the events to be filtered.

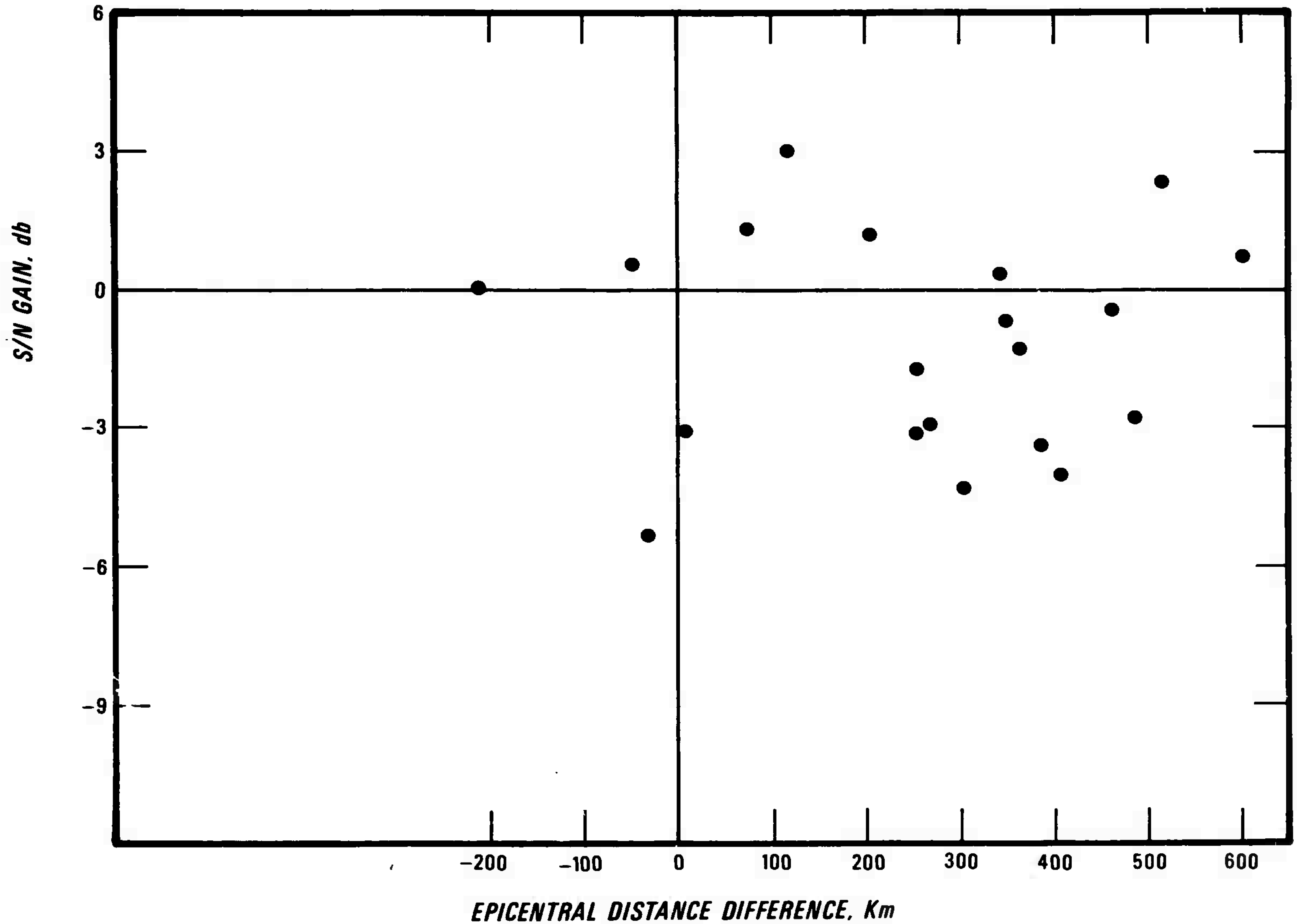

Figure 16. Gain in S/N achieved by whitening event 3 before filtering the Asian events.

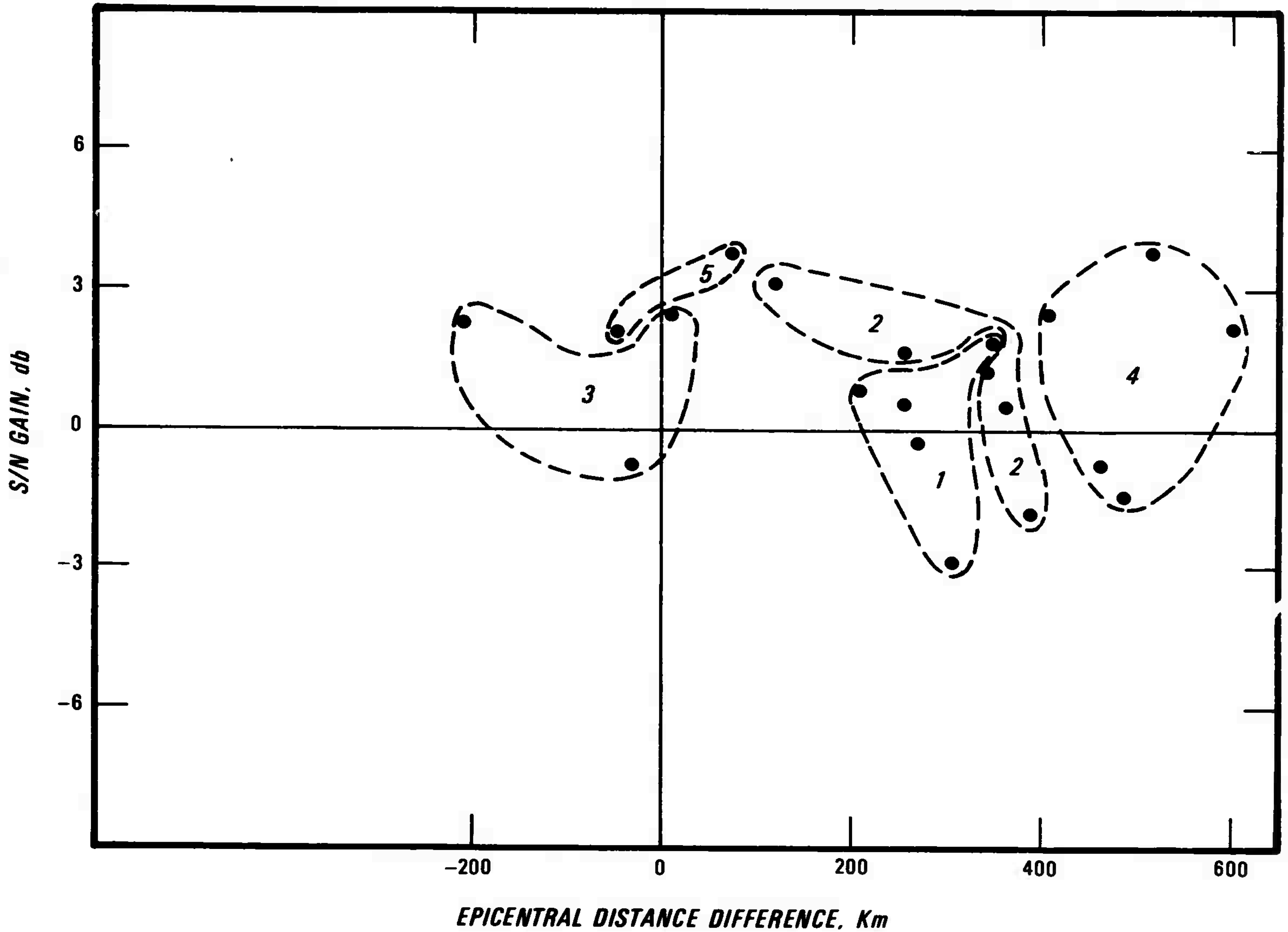

Figure 17. Gain in S/N achieved by whitening event 3 in the signal pass band only and suppressing all other harmonics before filtering the Asian events.

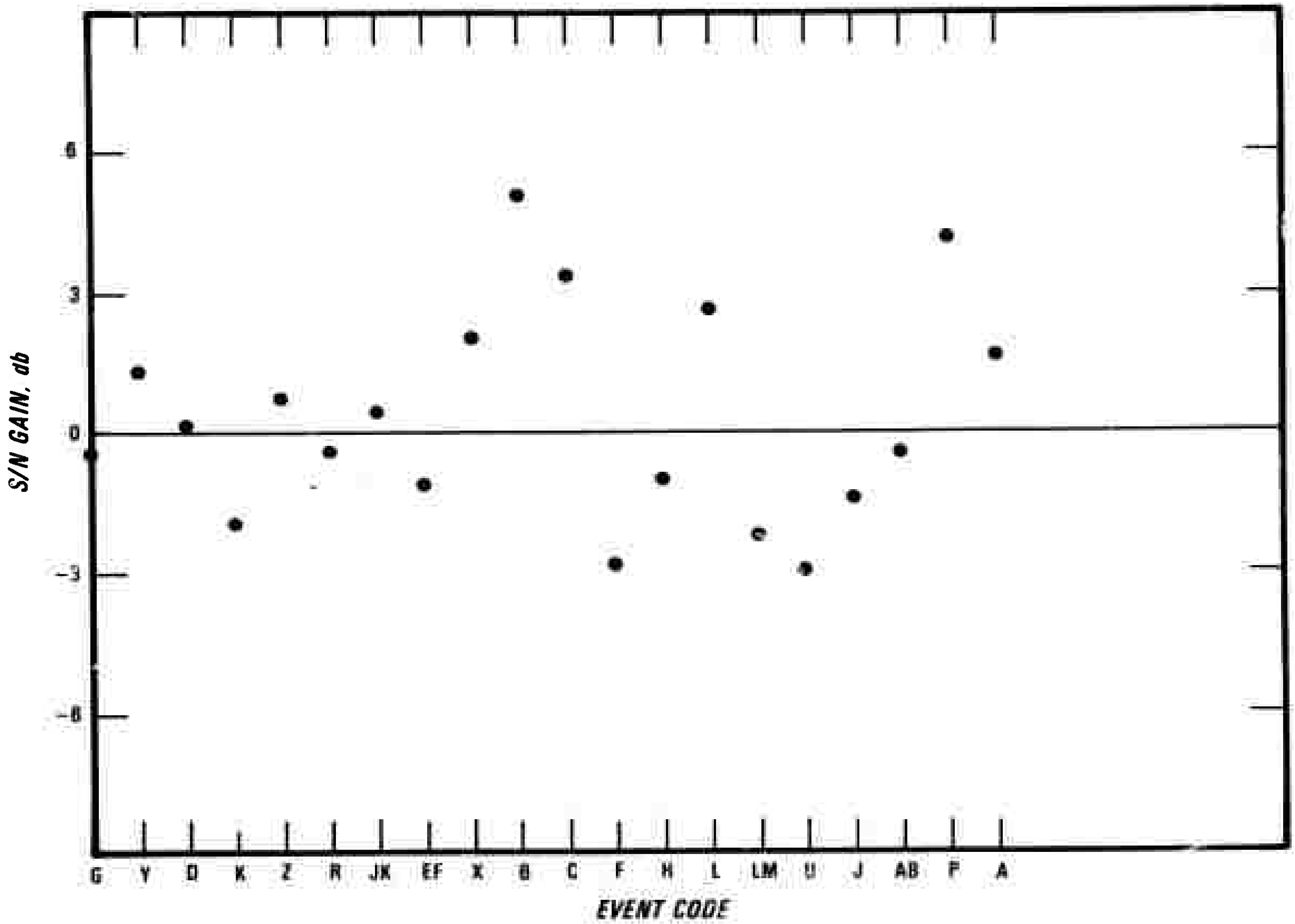

Figure 18. Gain in S/N achieved by using a chirp waveform rather than five real signals in match filtering the Asian events.

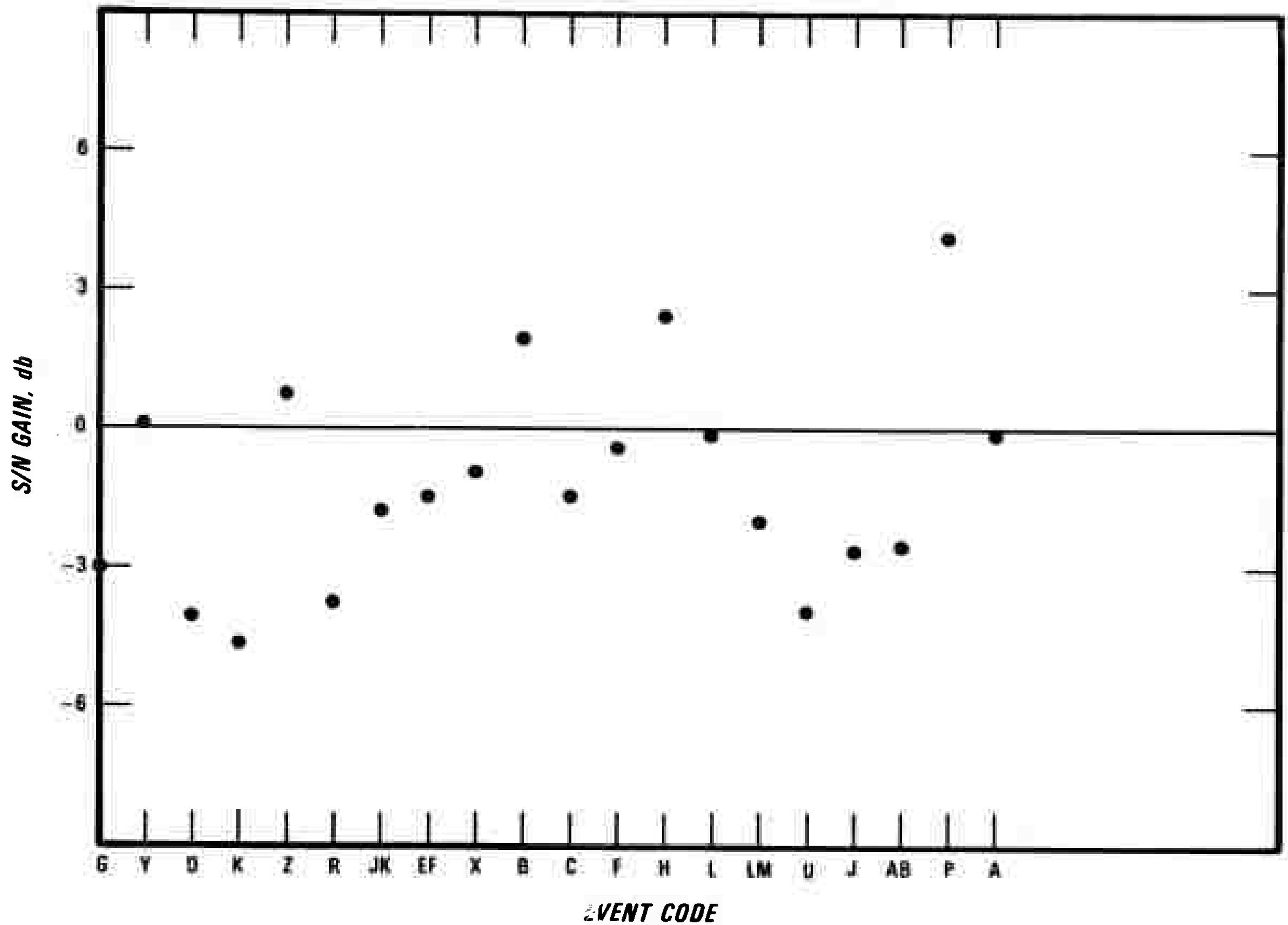

Figure 19. Gain in S/N achieved by using a whitened synthetic match filter constructed from Canadian-Shield phase velocities rather than five real signals in match filtering the Asian events.